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Challenges of recycling multiple scarce metals: The case of Swedish ELV and WEEE recycling

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ABSTRACT

Cars and electronic products are characterised by high metal complexity. Meanwhile, recycling industries are not fully aligned with this complexity, leading to losses of unique scarce metal resources. By utilising the technological innovation system framework we identify, and discuss implications of, factors that impact on recycling of some precious (gold, palladium, silver) and minor metals (gallium, tantalum) in printed circuit boards (PCBs) present in Swedish end-of-life cars (ELVs) and waste electrical and electronic equipment (WEEE). We conclude that while precious metals from WEEE PCBs are currently recycled, recycling precious metals from ELV PCBs will likely remain a challenge in the near-term due to recycling being blocked by the material composition of ELV waste, design of waste legislation, and by accumulated capabilities and business models in current recycling industries. However, some of these blocking factors are open to direct influence from national policymakers or industry actors and may thus be alleviated more easily. In contrast, recycling minor metals from ELV or WEEE PCBs will likely remain challenging also in the long-term due to a larger set of blocking factors. Alleviating these may require a substantial portfolio of metal-specific policies at national and supra national levels supporting the build-up of entirely new recycling value chains.

1. - Introduction

The production and metal complexity of cars and electronic products have grown over several decades (Edwards, 2004; Huisman et al., 2017; Restrepo et al., 2017). Today these products depend not only on base metals such as iron (Fe), aluminium (Al) and copper (Cu), but also on a diverse set of other metals that are geochemically scarce, and in many cases sourced from only a few locations worldwide (European Commission, 2017a, 2017b; Skinner, 1979). Some of these metals have been pointed out as critical to future welfare in regions currently lacking significant production capacity (e.g. EU, U.S. and Japan), as the elements are considered essential for realising a wide range of established and emerging technologies (European Commission, 2017a, 2017b).

Concurrently, recycling industries are not fully aligned with the complex waste streams of end-of-life vehicles (ELVs) and electrical and electronic equipment (WEEE). Far from all metal elements are recycled in a way that enables their unique properties to be used again, i.e. are functionally recycled (Andersson et al., 2017a; Graedel et al., 2011). Specifically, many scarce metals risk being lost by entering waste incineration or landfills, or by ending up dispersed in other recycled materials (Andersson et al., 2017a; Bigum et al., 2012; Nakamura et al., 2012; Ohno et al., 2014). This leads to essentially irreversible losses of metal resources, and unnecessary primary resource extraction with associated impact on the environment. Such losses, caused by insufficient recovery of scarce metals from End-of-Life (EoL) product components in today's recycling systems, have been highlighted as a global challenge by e.g. Awasthi et al. (2019), Graedel (2018), Graedel et al. (2011), Huisman et al. (2017) and Zeng et al. (2016). Thus, achieving recycling of scarce metals contained in complex products such as cars and electronic products is an issue of high societal relevance.

Recycling of ELVs and WEEE is currently performed in industry value chains where firms specialise in operations such as collection, dismantling, mechanical treatment and metal refining. From both waste streams, Fe, Al and Cu can already be functionally recycled to a significant extent. Additionally, some precious metals are functionally recycled from WEEE and catalytic converters in ELVs (Andersson et al., 2017a; Huisman et al., 2017). However, the literature suggests there is little or no functional recycling of precious metals from other ELV components or of non-precious scarce metals from any of the two waste streams (ibid.).

The prospect of realising recycling of currently not recovered metals may be influenced by numerous socio-technical aspects affecting

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different segments of today's recycling value chains. Such aspects may include the composition of waste, the availability of waste process technology and technical knowhow, the accessibility of metal markets and waste legislation (Andersson et al., 2017b; Graedel et al., 2011; Reck and Graedel, 2012; UNEP, 2013). However, studies considering entire industry value chains and a multitude of socio-technical aspects are still rare (Andersson et al., 2019). While innovation system and transitions research provide suitable frameworks to study such questions, hitherto mainly other empirical fields (such as renewable energy and electromobility) have been explored (ibid.). Here we adopt an adapted technological innovation system (TIS) approach, with the aim of identifying factors that impact on recycling of scarce metals from WEEE and ELVs. Additionally, we discuss implications for industry and policy if recycling is to be realised. The study is empirically limited to metals present in printed circuit boards (PCBs) in WEEE and ELVs. By exposing the TIS framework to a new empirical field, we also aim at contributing to the further development of the TIS approach.

2. Theoretical framework, method and scope

Within the growing literature on sustainability related innovation and transitions, the TIS approach has been fruitfully used to describe emergence and diffusion of technologies, and to identify supporting and blocking factors that can be strengthened or alleviated to spur development (Bergek et al., 2008a; Hekkert et al., 2007; Markard et al., 2012; Van Den Bergh et al., 2011).

The technology (T) in such studies can be defined in several ways. To adapt the TIS framework to the area of recycling, we take one step back from the common definition that the technology is a ‘product’ or ‘knowledge field’ (Bergek et al., 2008a), and start from the generic definition of a technology as a ‘means to an end’ (Arthur, 2009). In the present case, we study Ts that transform waste streams to refined metals. Each T consists of an actual or potential industrial system organised as an industry value chain (supply chain) (Sandén and Hillman, 2011).[1,2] For a T to function (as a means to a defined end), value chains need to be filled with aligned socio-technical components such as actors and networks; technical artefacts and associated knowledge; and cognitive, normative and regulative institutions that guide action (Bergek et al., 2008b). The TIS can then be thought of as a heuristic construct describing how a T emerges and develops (Hillman and Sandén, 2008).

The initial steps in an analysis include analytically delineating a T by defining socio-technical, spatial and temporal system boundaries. Additionally, an analytical performance goal is set for T, so that the status of T may be assessed. Subsequently, supporting and blocking factors are sought for to explain the status and to identify measures that may spur development. While studies with broad temporal boundaries typically also identify sequences of development, including different forms of circular causality (Suurs and Hekkert, 2009), we only indirectly refer to such dynamics in this study.[3] In Sections 2.1-2.2, we adapt these steps to study recycling of multiple metals from ELVs and WEEE, before describing our analytical and data collecting procedure (Section 2.3).

2.1. System delineation and system goal

We study value chains in which WEEE and ELVs are treated and PCB metals are refined. Among metals, we study gold (Au), silver (Ag) and palladium (Pd), hereafter treated as one group and referred to as *precious metals*. Additionally, we study gallium (Ga) and tantalum (Ta), referred to as *minor metals*.[4] These selections are made to illustrate challenges and opportunities involved in recycling multiple scarce metals from EoL products.

Subsequently, we can for analytical purposes define the socio-technical boundaries of four Ts, by specifying the transformation of waste inputs to metal outputs taking place within each (Table 1): WEEE to precious metals from PCBs (T_{F1}), WEEE to minor metals from PCBs (T_{F2}), ELVs to precious metals from PCBs (T_{F3}) and ELVs to minor metals from PCBs (T_{F4}). We refer to these as *focal* Ts. Each is assigned the goal of outputting the entire amount of the metal contained in the PCBs of its input, i.e. achieving a recycling rate of 100%. Note that these are analytical goals, which do not have to be shared by actors in studied value chains. Importantly, also note that although some segments of the real-world value chains that the Ts represent are the same, the Ts are treated as separate technologies since they may perform differently according to their analytical goals. While basically all technologies share elements, only a few TIS studies have highlighted this aspect (Haley, 2015; Sandén and Hillman, 2011). In this case it is a salient feature. Furthermore, note that the Ts are not defined based on a certain constellation of actors (which is sometimes the starting point in TIS studies).[5] Here, one actor (firm) may be part of several Ts.

There are also numerous other identifiable technologies, which are likely to interfere with focal Ts due to sharing segments of the same value chains. These include value chains utilising other inputs, such as non WEEE or ELV waste or primary raw materials, to output the same metals as focal Ts, other metals or material streams used outside studied value chains. We define some such Ts and refer to them as *contextual* Ts (see $T_{C1\text{-}8}$, Table 1).[6] See Fig. 1 for additional clarity.

Sweden is chosen as spatial boundary for all systems, partly to support data collection and partly because it provides an illustrative case. Temporally, the study mainly uses data representing ca 2017.

By delineating Ts in this way, we separate them horizontally from other value chains and vertically from upstream and downstream processes. Hence, we consider processes like car and electronics production, and supply and use, as upstream structures outside the system boundaries, and metal markets (metal buyers) as external downstream structures.

2.2. Supporting and blocking factors

A T's capability to fulfil an analytical goal depends on its setup of socio-technical system components. Not all Ts have ‘working’ setups in this regard and are thus not equally mature in development. The TIS can be conceived as the system that governs, or describes, the development (Hillman and Sandén, 2008).

The TIS causally links the development of a T to a set of factors that may be internal or external to the T. A variety of such factors has been identified in TIS literature, sometimes captured as socio-technical ‘structural components’ (individual or networked actors, artefacts, or various types of knowledge or institutions) and sometimes as

[1] In principal this is not as different from the common definition of a T as it might look, since a product always can be represented by the underlying industrial system producing it.

[2] Throughout the text we use the term ‘value chain’ when referring to an industry-level value chain, which allows for value creation beyond the single firm.

[3] Circular causality comes in two basic forms Sterman (2001). Studies based in neoclassical economics typically focus on balancing (negative) feedback loops due to limitations in demand or supply, while studies rooted in innovation economics tend to focus on reinforcing (positive) feedback loops due to economies of scale and learning. With an extended temporal, geographical or sociotechnical scope both these forms of circular causality could fruitfully be included, but at the cost of increased analytical complexity. This is beyond the scope of this study.

[4] There is a multitude of scarce metals in PCBs. The selected metals should be taken as examples.

[5] See e.g. the definition of technological systems in the seminal paper by Carlsson and Stankiewicz, (1991).

[6] We do not define all possible analytical contextual Ts, only some illustrative cases.

Table 1
Delineations of focal and contextual Ts in this study, denoted by index F (T_F) and C (T_C) respectively. Socio-technical boundaries are defined by inputs and outputs. Spatial and temporal boundaries are Sweden and 2017 conditions, respectively. T_{F1}-T_{F4} are assigned the goals of fully recovering the metals described by system outputs.

INPUT	OUTPUT						
	Precious metals from PCBs (Au, Ag, Pd)	Minor metals from PCBs (Ga, Ta)	Precious metals (Au, Ag, Pd)	Minor metals (Ga, Ta)	Copper (Cu)	Other metals (Pb, Zn)	Material streams used outside studied value chains
WEEE	T_{F1}	T_{F2}	–	–	T_{C1}	–	T_{C2}
ELV	T_{F3}	T_{F4}	–	–	T_{C3}	–	T_{C4}
Other (industrial waste other than WEEE and ELVs, or primary raw materials)	–	–	T_{C5}	T_{C6}	T_{C7}	T_{C8}	–

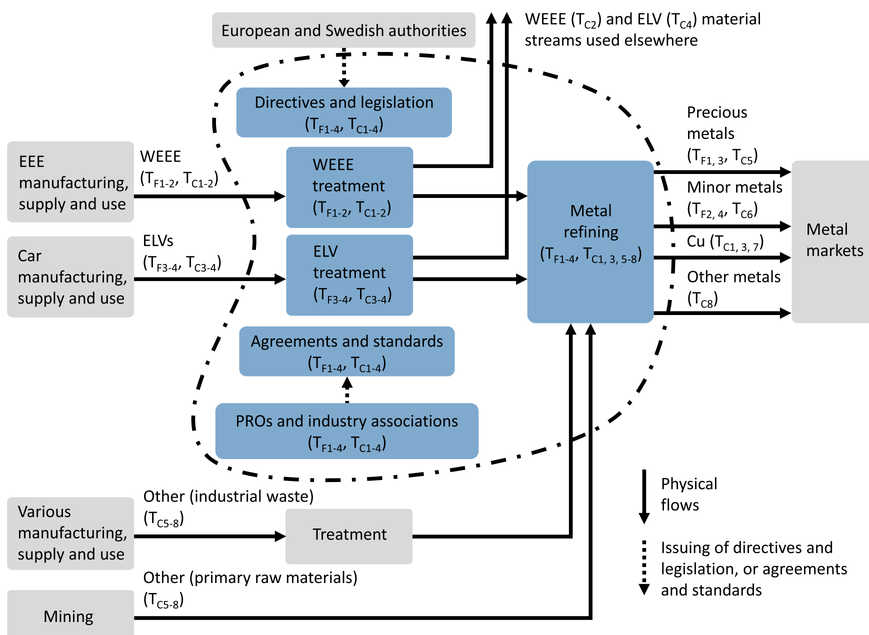

Fig. 1. Representation of current and potential Swedish value chains related to WEEE and ELV treatment, and refinement of PCB metals. The delineated components represent focal and contextual technologies.

innovation system 'functions' (development processes, in which e.g. new knowledge or a market specific to a T is created) (Bergek et al., 2008a; Hekkert et al., 2007). A general observation is that configurations of components can take part in functions and thereby develop a T. Some configurations may instead block development. Hence, there is a wide scope for what qualifies as a factor. Nevertheless, we can specify two elemental groups expressed in literature: Means (capabilities and resources) and incentives (motivation or enforcement) (see e.g. Lall (1992)). Means stem from access to knowledge, technical hardware, raw materials and human and financial resources. Incentives depend on the market situation, expectations and visions of future developments, and regulative and normative institutions. Furthermore, internal and external factors are distinguished between since the possibility for actors to influence them differs, and because the factors affect development differently. Internal factors are more open to influence by actors in or at the fringe of a T. A change to internal factors may set in motion processes of circular causality, which if strong enough can propell the development of a T independenty of external factors. External factors are instead seen as affecting development, but not significantly being affected by it. An early development is typically determined by external factors, but as the T matures internal factors grow in importance (Arthur, 1988; Bergek et al., 2008b). Note that the difference between internal (T specific) and external factors is not always clear-cut. Rather, it is a scale from very T specific (fully dependent on T development) to more general (marginally dependent).

In the present case we focus on a limited set of external factors: the magnitude and composition of waste streams; the economic value of those same waste streams; long-term metal price trends; access to markets; and guidance from policy-making on scarce metals. Among internal factors, we focus on technology specific regulations; value chain relations and business models; the historical heritage of physical infrastructure, knowledge base and actor network structure; and the industry's revealed goals and associated investment in new capability. The selection is informed by a previous study on historical development of ELV recycling (Andersson et al., 2017b), and based on the empirical findings in this study. While we believe this set captures the most salient factors at an industry level of observation, we do not preclude the possibility that other factors might be of importance. Furthermore, since the underlying value chains of the Ts in this study are entangled and interdependent, we define 'external factors' as factors outside the boundaries of all Ts, stemming from elements upstream and downstream the value chains, and/or being assumed as generic and independent of system developments (within the temporal system boundary). Factors more specific to T_{F1}-T_{F4}, being part of any or all focal Ts are termed ‘internal factors’. Note that we primarily focus on identifying current factors (as of ca 2017), not on describing potential future development scenarios caused by these factors.[7]

2.3. Analytical procedure and data collection

In Chapter 3, we describe the current state of real-world value chains that $T_{F1\text{-}4}$ and $T_{C1\text{-}8}$ represent, and assess the maturity (goal fulfilment) of focal technologies ($T_{F1\text{-}4}$). In Chapters 4 and 5, we identify supporting and blocking factors that can explain differences in maturity levels. We then discuss implications for industry and policy if maturity levels are to be raised and recycling realised (Chapter 6), and draw conclusions (Chapter 7).

Among data sources used are publicly available reporting by companies, industry associations, research organisations, government agencies, public and governmental bills and official inquiries. Some data was collected through interviews with qualified experts, positioned in different parts of the Ts. Interviews were open-ended and conducted face-to-face or by phone. Site visits at recycling facilities were made to enrich the understanding of firm rationalities and capabilities.

3. Description and maturity assessment of focal technologies

The value chains corresponding to delineated Ts (Table 1), can be observed inside the boundary presented in Fig. 1. Since not all technologies are fully developed, the figure contains both actual and potential flows. EoL products are processed within *WEEE treatment* and *ELV treatment*. These two EoL products are covered by individual European extended producer responsibility (EPR) directives, implemented as Swedish legislation. Legislative adherence is managed by producer responsibility organisations (PROs) through industry agreements and standards. Extracted PCB materials are sent to *metal refining*. Note that some materials streams from WEEE and ELV treatment, such as ELV spare parts and different raw materials are not sent to the studied metal refining facility but to destinations outside the boundary. Upstream the boundary, there are manufacturing, supply and use of EEE and cars, various manufacturing industries and mining operations.[8] Downstream, we find metal markets. Finally, European and Swedish authorities forming the aforementioned policy are conceptualised as outside the boundary. Sections 3.1-3.3 provide details on structures within the boundary.

3.1. WEEE treatment

Most WEEE is collected through municipally owned recycling centres, and then shipped to WEEE treatment companies for dismantling and automated treatment (IVL Swedish Environmental Research Institute, 2015a, c). WEEE is in practice treated in four streams containing light sources, large domestic appliances (e.g. washing machines and cooking stoves), fridges and freezers, and various electronic devices (e.g. mobile phones, computers and vacuum cleaners) (ibid.). During dismantling, some parts covered by WEEE legislation are removed manually. If deemed economically viable, some additional items are also dismantled (Heed, 2017; Sjölin, 2017). The remains are sorted into more homogenous streams and shipped to automated treatment, i.e. shredding followed by various sorting operations such as magnet and eddy-current separation and density baths (El-kretsen, 2018; Heed, 2017; Sjölin, 2017). The metal-rich fractions generated are sold to metal refineries. The legal requirements put on EEE manufacturers and retailers are managed by two PROs, of which one takes part in organising the absolute majority of all WEEE flows (IVL Swedish Environmental Research Institute, 2015a, c). The European WEEE directive is implemented in adapted form as Swedish law, which currently includes product level recycling targets and procedural requirements (Swedish EPA, 2017c; Swedish Ministry of Environment and Energy, 2014).[9]

3.2. ELV treatment

ELVs are initially supplied to dismantling firms by private individuals or insurance companies (Andersson et al., 2017a). Here, according to Swedish ELV legislation consisting of recycling targets[10] and procedural requirements, liquids are removed along with hazardous components and components such as the catalytic converter, wind shield and tyres (Swedish Ministry of Environment and Energy, 2016; 2018). Spare parts that may be sold are removed along with recyclable components rich in predominantly Al, Cu or Fe. Typically, electronic components cannot be used as spare parts or are costly to remove and ship, and are therefore left in ELVs. The remaining ELV is sold to automated treatment companies. While there are roughly 300 small-scale dismantling firms, primarily three companies are involved in automated treatment at large-scale facilities aimed at shredding and separating materials. Fe- and Al-rich raw materials are isolated and sold to metal refineries outside studied value chains. Other raw materials are recycled as construction materials, and some are incinerated or landfilled at a cost (Andersson et al., 2017a). Some copper-containing fractions can be generated, of which some may reach the metal refinery in focus of this study (Section 3.3). One PRO manages the legal requirements and is owned by the Swedish Car Recyclers Association (SBR) (representing car dismantling firms) and the largest automated treatment company.

3.3. Metal refining

In Scandinavia, one refining and mining company is a dominating actor in refining Cu, Au, Ag, Lead (Pb), Zinc (Zn) and platinum group metals (PGMs). It represents a significant customer for actors generating primary and secondary raw materials rich in these metals. Primary raw materials are sourced from the actor's own mining operations and from external actors, and secondary raw materials are sourced from Swedish and foreign waste treatment companies (Boliden, 2012; Schweitz, 2017). The one smelter utilising PCBs as raw materials, located in northern Sweden, is one of the largest consumers of WEEE raw materials worldwide (Boliden, 2016a; Schweitz, 2017). Cu, Zn, Pb, Au and Ag are produced as refined metals while PGMs are sold in intermediate form (Hjelmstedt, 2017).

3.4. Maturity assessment of focal technologies

Functional recycling of precious metals from WEEE exists already (Sections 3.1 and 3.3). Hence, T_{F1} is relatively mature. The focal Ts T_{F2}-T_{F4} are further away from fulfilling their analytical system goals, evidenced by that PCBs are not processed in WEEE treatment with the aim of recovering minor metals (T_{F2}) and that PCBs are not processed at all

[7] By defining metal markets, and hence metal prices as external, and by limiting the temporal boundary, we do not consider secondary effects from increased output of recycled metals mediated by changed market prices. For example, estimating effects of price elasticities of demand and supply on metal markets is outside the scope of the study.

[8] Note, however, that manufacturers and suppliers of cars and EEE are represented in focal systems as members of PROs.

[9] The EU directive also includes collection targets, but as Swedish collection historically has been high the Swedish implementation requires producers only to report statistics on collection.

[10] 95% of the discarded car must be reused, recycled or incinerated with energy recovery, out of which 85 percentage must constitute reuse and recycling.

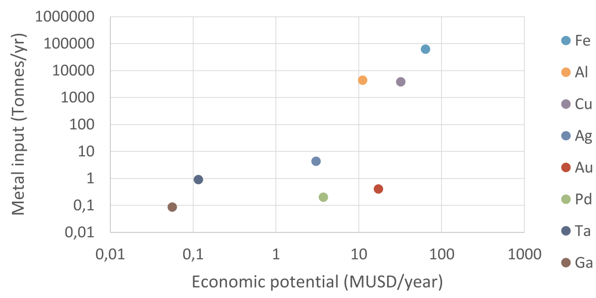

Fig. 2. Estimated input to WEEE treatment in 2015 of precious metals, Al, Cu and Fe based on data provided by El-kretsen (2016), and of minor metals based on Huisman et al. (2017) and the ProSUM project (2018). Economic potential based on U.S. spot prices in 2010 (U.S. Geological Survey, 2013).

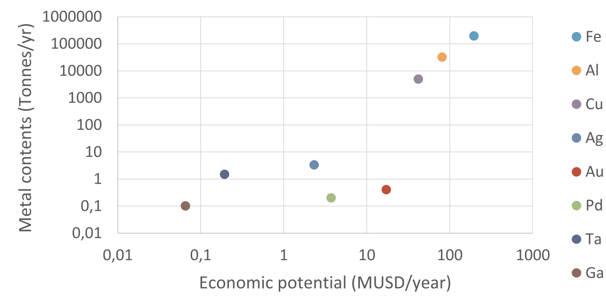

Fig. 3. Estimated contents of precious and minor metals, Al, Cu and Fe in a hypothetical future ELV fleet made up of new cars representative for the Swedish market. Ag, Pd and minor metals based on average quantities from Andersson et al. (2017a). Cu based on average quantities from Cullbrand and Magnusson (2012). Au based on Restrepo et al. (2017). Al and Fe based on Jensen et al. (2012). Economic potential based on U.S. spot prices in 2010 (U.S. Geological Survey, 2013).

in ELV treatment (T_{F3} and T_{F4}). Additionally, minor metals are not separated in the refinery (T_{F2} and T_{F4}). In Chapters 4 and 5, we investigate what external and internal factors respectively that can explain the observed difference between T_{F1} and T_{F2}-T_{F4}, and what may be required to develop the less mature systems.

4. External supporting and blocking factors

4.1. Metal contents and composition of WEEE and ELV flows

Recovering the focal metals is made difficult by the variety and difference in mass of metals and materials contained in WEEE and ELVs. PCBs contain dozens of metals, typically present in milligrams per unit (Holgersson et al., 2018). Furthermore, PCBs only make up a small fraction of the products they are integrated in.

The total mass of annual WEEE and ELV flows in Sweden are of the same order of magnitude. ELV input amounts to 230 000 tonnes per year, about 1.5 times the amount entering WEEE treatment (El-kretsen, 2016; Eurostat, 2018). The exact material compositions of these inputs are difficult to specify due to the large variations in EEE and car configurations, but rough numbers can be estimated. Fig. 2 (vertical axis) shows an estimate of annual input to WEEE treatment of precious and minor metals, Al, Cu and Fe.[11] Much of the precious metals and Ta likely originate from PCBs, since there are no other evident applications. Ga may, however, also be used in light emitting diode (LED) applications (European Commission, 2017b), not necessarily tied to PCBs. Fig. 3 (vertical axis) shows our estimate of the total contents of precious and minor metals, Al, Cu and Fe in ELV flows arising in the late 2020s to early 2030s, made up of cars representative of the Swedish car market. Major shares of the precious and minor metals in ELVs likely originate from PCBs, except Pd which is also found in catalytic converters and Ga which may appear in LED applications (Andersson et al., 2017a).

Both streams approximately contain between 0.1 and 10 tonnes per year of each precious and minor metal, representing concentrations in products of some 1–100 ppm. Furthermore, it is noticeable how the mass of precious and minor metals is dwarfed by Al, Cu and Fe in both flows. In addition, both WEEE and ELVs contain considerable amounts of other materials such as plastics and glass. Recovering the relatively small quantities of precious and minor metals, is thus bound to be relatively costly and to incentivise less attention compared to recovering concentrated high-volume metals. This serves as a blocking factor affecting all $T_{F1\text{-}4}$, and concurrently as a factor supporting $T_{C1\text{-}4}$.

4.2. Economic potentials of system inputs

The incentive to develop each focal technology is likely highly influenced by the economic potentials of inputs, i.e. the economic value of metals in an input, if metals were to be sold. Each focal technology is also affected by economic potentials supporting other technologies. For instance, the value of another metal in the same stream or of metals in other streams, may lead to developments that occur at the expense of focal technologies.

The relatively small mass of precious and minor metals imply that high prices are needed if potentials are not to be overshadowed by greater potentials provided by other metals. Assuming world metal prices, ELV Fe and Al (T_{C4}) would make up some 80% of the total metal value of ELVs, Cu (T_{C3} or T_{C4}) roughly 10% and precious metals (divided between T_{F3} and T_{C4}) 10% (Fig. 3, horizontal axis). The corresponding shares in WEEE input streams are 60% (T_{C2}), 25% (T_{C1} or T_{C2}) and 15% (T_{F1}), respectively (Fig. 2, horizontal axis). The economic potential of minor metals (T_{F2}, T_{F4}) is insignificant in comparison (Figs. 2–3).[12] Non-metals (such as plastics) typically have low value (Andersson et al., 2017a). Thus, although Figs. 2–3 indicate that the potential of non-recovered precious metals in ELVs is comparable to what is currently recovered in WEEE treatment, the potential of Fe and Al is higher in ELV treatment than in WEEE treatment.

In the refining segment of the value chains, other metals than focal metals are refined and both secondary and primary raw materials are used as inputs. Hence, focal metals compete with other metals and with other input streams. Currently Ag, Au, Cu, Pb and Zn are all considered as main products, while PGMs are considered as by-products (Hjelmstedt, 2017). Minor metals are not refined. Thus, the economic potential of base metals is deemed favourable (T_{C1}, T_{C3}, $T_{C7\text{-}8}$), the potential of precious metals somewhat less so indicated by PGMs being by-products (T_{F1}, T_{F3}, T_{C5}), but unfavourable for minor metals (T_{F2}, T_{F4}, T_{C6}). Regarding the currently refined precious metals, some 50w% and 70w% of the Au and Ag output respectively originate from primary sources (Boliden, 2016b). Consequently, although these shares imply that primary raw materials provide a large economic potential (T_{C5}), the potential is far from large enough to completely overshadow the potential provided by precious metals in secondary raw materials (T_{F1} and T_{F3}).

In conclusion, although the economic potentials of base metals in

[11] Regarding precious metals, Al, Cu and Fe, Fig. 2 illustrates input after any losses occurring during treatment. Note that such losses can be large for small-quantity metals (UNEP, 2013), and that the true input likely is higher than the values displayed. However, input quantitates similar to those displayed have been reported by Huisman et al. (2017) and the ProSUM project (2018).

[12] Note that an underlying assumption behind the debate on scarce metals, is that current prices do not reflect their long-term value.

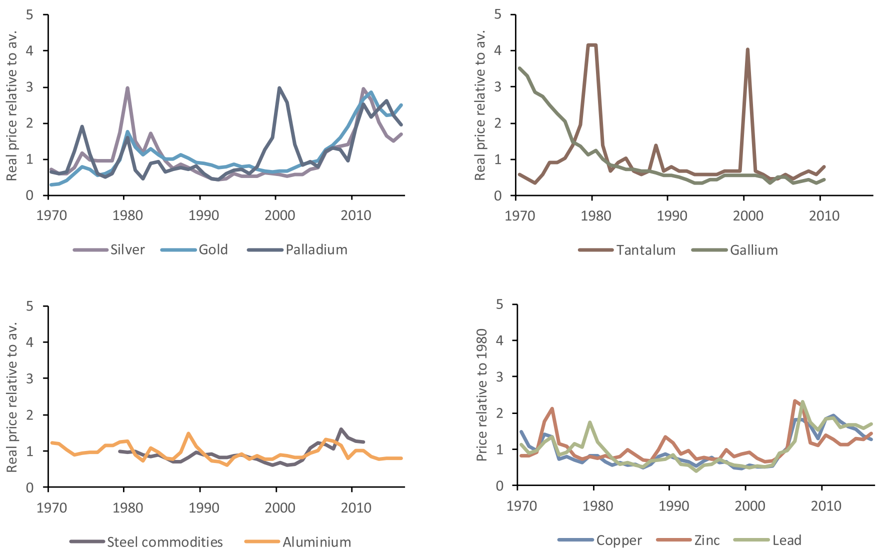

Fig. 4. Real price relative to the average in the displayed period, of precious metals (Ag, Au, Pd), minor metals (Ga, Ta), Al and steel commodities (Fe), and base metals refined in studied value chains (Cu, Pb, Zn). Data on Ag, Al, Au, Cu, Pb, Zn and steel commodities provided by World Bank Group (2017), on Ga, Pd, and Ta by U.S. Geological Survey (2013).

studied waste streams provide incentives for recycling WEEE and ELVs, they may also focus the direction of interest of actors away from precious and minor metals, i.e. T_{C1-4} may be favoured over T_{F1-4}. Nevertheless, precious metals in both WEEE and ELVs do provide economic potentials (working as a supporting factor of some strength for T_{F1} and T_{F3}), while the low current economic potentials of minor metals in both streams are clearly a blocking factor for T_{F2} and T_{F4}. Finally, although the potentials of precious and base metals in other streams provide incentives to source these streams by the metal refining actor (T_{C5}, T_{C7-8}), the potentials of precious metals in PCBs from WEEE and ELVs are likely high enough for both streams to be sourced as well (even though only WEEE PCBs are currently sourced). This seemingly is not the case for minor metals (T_{F2}, T_{F4}, T_{C6}).

4.3. Long-term metal price trends

Long-term increasing metal price trends will raise expectations and provide incentives for investment in the focal technologies. Such trends are of particular importance to automated treatment and refining activities, where costs of building physical capital are large (Reuter et al., 2006; UNEP, 2013). Fig. 4 depicts price trends (real prices) over four decades for precious, minor and base metals.[13] Compared to base metal prices, precious and minor metal prices are more volatile. Still, precious metal prices have about doubled since the turn of the century (disregarding the price peak of Pd in 2000). The Ga price instead fell in the 1970s and 1980s, but has remained relatively stable since 1990, while the Ta price shows a few dramatic spikes from a stable baseline.

The recent price increase of precious metals, Cu, Pb and Zn compared to Al and steel (Fe) could work as a supporting factor for recovery of precious metals from PCBs (T_{F1}, T_{F3}), although it may also incentivise actors to focus on larger components rich in Cu (support T_{C1-4}) or other streams rich in these metals (support T_{C5}, T_{C7-8}). In contrast, the long-term decline and stabilisation at a low level of the Ga price, and only occasional price spikes in Ta, do not provide additional incentives to recover Ga and Ta respectively (price trends block T_{F2} and T_{F4}).

4.4. Metal market design

The economic arguments in Sections 4.2-4.3 assume global market prices. However, metals are typically not sold by the studied refining actor on one big market with flexible buyers and sellers. Instead, outputs are sold to a limited number of industrial firms, with whom long-term relationships have been established (Boliden, 2016a). For the refined base metals (Cu, Pb, Zn) and the remaining refined metals (Au, Ag, PGMs) there exist open market places like the London metal exchange and the London bullion market association respectively, but selling to these is considered as a last resort since industrial customers historically have provided a more profitable and stable outlet (Hjelmstedt, 2017). Moreover, these customers are located mainly in northern Europe, since a short geographical distance reduces transport costs and increases revenue (ibid.). Hence the market place for the current outputs of the refinery is characterised by a stable set of regional customers with an option to trade on an open platform when needed.[14]

If the refining actor was to sell minor metals, there are at least four market hurdles. First, it needs to form new relationships, second, there are not many European manufacturers using substantial quantities of minor metals (European Commission, 2017a, 2017b), third, minor metals are not traded on major metal exchanges, reducing the number of outlets and the possibility to hedge against risks, and fourth, there is in and outside EU already existing refining capacity to varying degrees (European Commission, 2017b), which may influence negatively on access to existing market places. In conclusion, this market design incentivises, i.e. supports, refining precious metals (T_{F1}, T_{F3}), other refined metals (T_{C1}, T_{C3}, T_{C5}, T_{C7-8}) but not minor metals (i.e. it blocks T_{F2}, T_{F4}, T_{C6}).

4.5. Political visions and policy-making

Public policy may affect technological development. For example, government bodies may engage in forming visions by creating roadmaps and targets. Such articulated visions could be a precursor of several types of more tangible policy, which incentivise development or enhance capabilities of specific technologies. Here, we briefly look at political bodies that in recent years have been involved in broad policy-making relevant to recycling of scarce metals.

At the national level, the Ministry of Environment and Energy (MoEE) and Ministry of Industry and Trade (MoIT) hold the main responsibilities for managing waste and metal scarcity issues. Most recently, the MoEE investigated strategies for promoting a circular

[13] We find no clear evidence in these trends that would change conclusions made in Section 4.2.

[14] In addition to being last resort market places, metal exchanges are used to reduce financial risks of trading metals. For every trade of a physical metal, the opposite trade is made on a metal exchange (Hjelmstedt, 2017), creating a zero-sum transaction (off-set hedging).

economy (Swedish Ministry of Environment and Energy, 2017). The investigation points to needs of extensive changes in policy-making on waste prevention, reuse and recycling, such as increased coordination between authorities and changes to tax systems in favour of decreasing material use and waste. Although recycling of scarce metals is mentioned as a relevant policy issue, the need for any national initiatives is largely written off (ibid). Furthermore, the Swedish EPA, subordinated to the MoEE, issues national waste management plans. Previous plans have prioritised waste prevention and collection, counteracting the spread of hazardous substances from EoL components, and illegal waste exports (Swedish EPA, 2012). WEEE and to a lesser extent ELVs have been prioritised in these plans, but mainly waste collection and compliance of industry actors with regulation have been targeted, not recovery of metals (Swedish EPA, 2012). Current plans express a need for more clearly formulated targets, but as of yet there are none related to scarce metal management (Swedish EPA, 2017a, b). As part of national industrial development programmes, the MoIT has investigated potentials to improve management of metals and minerals, including scarce metals, but these mainly address primary resources (Geological Survey of Sweden, 2014, 2018; The Swedish Agency for Growth Policy Analysis, 2017). Consequently, although investigations are made, and some target areas exist, there are yet no visions of how to enable working value chains for specific metals.

At the EU level, under the umbrella of the Raw Materials Initiative (RMI), recycling of scarce metals is more clearly targeted. The EC regularly publishes reports on critical raw materials (European Commission, 2010, 2014, 2017a), where recycling is highlighted as a strategy to decrease scarce metal supply risks. In EU circular economy initiatives, metal recycling is framed as an industrial development issue (European Commission, 2018). The RMI is also a source of more tangible policy in that it provides research funding. However, much of the funding is allocated to technical development, while product or system centric views taking into account larger parts of value chains are largely not represented (Løvik et al., 2018). Thus, although these initiatives indicate that visions are being formulated at the EU level of how to manage scarce metals, and more tangible policy is in place, directives have not yet been affected.

In conclusion, policy-making on scarce metal recycling is in early stages. National waste plans exist, in which waste management of WEEE and to some extent ELVs are prioritised. These plans could support recycling of focal precious metals (T_{F1}, T_{F3}) and other metals and materials in WEEE and ELVs ($T_{C1\text{-}4}$), since many components of fully formed value chains exist for these outputs. At the EU level, visions and more tangible policy exist, but they seemingly do not yet impact on studied value chains. Overall, few articulated visions or policies exist targeting individual scarce metals and entire value chains, and there is no political body that has a clear mandate to form a coherent policy portfolio aimed at developing such value chains. Thus, current policy-making cannot be said to support recycling of minor metals (blocks T_{F2} and T_{F4}).

5. Internal supporting and blocking factors

5.1. EPR requirements

Industry actors are mandated to perform certain treatment procedures according to EPR legislation. The EPR legislation is technology specific and, hence, we consider it as an internal factor. A key observation is that the procedural requirements on WEEE and ELV treatment are specified differently, which imply that they incentivise recovery of components and materials differently.

WEEE procedural requirements are specified by the Swedish EPA in accordance with the WEEE directive and include among other things removal, and treatment of PCBs from mobile phones regardless of size and any PCB larger than 10 cm^2 (European Parliament and Council, 2012; Swedish EPA, 2017c). This is required mainly due to concerns over potential hazardous substances in PCBs (European Parliament and Council, 2012), but in practice means a component level specification that also affects recycling of all PCB metals.

ELV legislation include an extensive list of procedural requirements (European Parliament and Council, 2000; Swedish Ministry of Environment and Energy, 2018). To promote metals recycling, catalytic converters and metal components containing Cu, Al, or magnesium need to be recovered through dismantling or automated treatment (ibid.). Like WEEE requirements, ELV requirements target hazardous substances but do not specifically single out PCBs.

Neither of the two sets of legislation directly target the focal metals of this study, and there are no requirements on functional recycling of any metals, i.e. processes that secure metal properties for continued use. Although recycling targets exist for both waste categories, they predominantly affect materials and components of large mass ($T_{C1\text{-}4}$) since targets are specified as weight percentages.

Consequently, the specification of PCBs in WEEE EPR requirements can be said to support recycling of precious and minor metals ($T_{F1\text{-}2}$), while ELV EPR regulation does not (blocks $T_{F3\text{-}4}$).

5.2. Business models

Within studied value chains there are internal supplier-buyer relationships and financial transactions, which affect incentives to engage with focal technologies. Over time, such relations and transactions, i.e. the ‘way to do business’, may become institutionalised norms of behaviour, or ‘core logics’, that lock in a certain structure (Sarasini and Linder, 2017; Zott et al., 2011) independently of other factors.

Financial transactions in WEEE treatment relies to a large extent on procurement procedures organised by the largest PRO, which procures collection and treatment services to secure compliance with EPR regulation. Through procurement, the value of two economic components are settled: (1) the value of the service of taking care of waste (a cost from the perspective of the PRO), and (2) the value of metals contained in WEEE (revenue from the perspective of the PRO) (see Fig. 5). The agreed upon service value is payed for, and a share of the agreed upon metal value is acquired by, the PRO. The metal value is based on world metal prices, and the metal contents of WEEE products are investigated by the PRO and WEEE companies (Benson, 2017; IVL Swedish Environmental Research Institute, 2015a, c). Consequently, in the case of services being valued higher than the metals, the net result is payment by the PRO, but payment in the opposite direction in the reverse situation. In addition to these transactions, the PRO is financed by member fees, but repay members if sufficient financial surplus is achieved. Hence, there is a considerable apparatus in place for establishing the contents and value of metals in waste flows, and managing the financial implications of EPR legislation.

In ELV treatment, the PRO is not as directly involved in financial transactions. Instead, there is an exclusive partnership between the car industry and the PRO, requiring the PRO to fulfil EPR requirements in exchange for PRO members retaining any value that can be extracted from ELVs. As part of this setup, actors in the value chain pay each other directly (Fig. 5). In the dismantling step, ELVs from private individuals are not accompanied by any financial transactions, while ELVs provided to dismantlers by insurance companies are paid for by the dismantler (Andersson et al., 2017a). Additionally, dismantlers involved in selling spare parts to insurance companies typically have this as their main income (applies to roughly 30% of the annually generated ELVs) (Jensen et al., 2012). Beyond this income, the dismantled ELV and any removed metal-rich components are sold to automated treatment companies, based on the value of metals contained minus the value of treatment services provided by automated treatment companies (Heed, 2017).

In metal refining, raw materials are purchased from suppliers at prices based on the value of contained metals minus the value of refining (Boliden, 2016a). Beyond charging suppliers for refining metals,

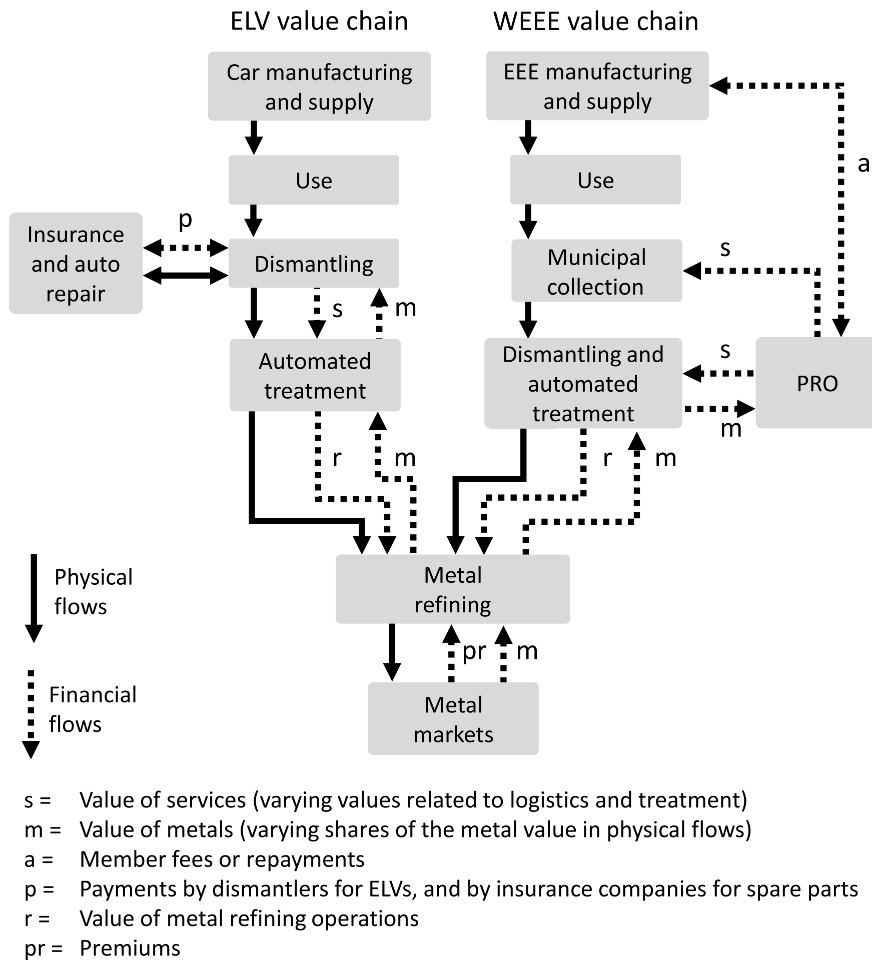

Fig. 5. Simplified illustration of activities, physical and financial flows in value chains related to recycling of metals from ELVs and WEEE.

the refinery creates revenue from any metal that can be produced and sold beyond what is agreed upon with suppliers, and from so-called premiums (ibid.). Premiums are paid by customers (on top of the metal price) for the service of being supplied with the finished product. Additionally, metal exchanges are actively used to reduce the financial risk of these trades.[15]

These differences mean that actors are exposed differently to financial risks and rewards. In WEEE treatment, the risk to individual actors of being exposed to high recycling costs are distributed on many actors. The PRO absorbs some costs associated with meeting procedural requirements and recycling targets, and receives compensation from EEE manufacturers and suppliers. Regarding PCBs, since these are included in EPR regulation, the cost of recovering them will ultimately have some financial backing.

In ELV treatment, treatment firms carry all risks and rewards. The potential downside is the lack of external backing if financial margins erode. For example, if treatment costs increase due to increasing material complexity of ELVs (which has been the general trend over the last decades) or stricter legal requirements, or if metal prices decrease or become volatile there is no structure in place to financially secure recycling. Instead, since both metal refining and automated treatment companies retain portions of the value of the materials they sell, and transfer the rest along with treatment costs to suppliers, the remaining value as well as some costs of untreatable materials will go upstream until reaching dismantlers. Especially for dismantlers not benefitting from selling spare parts, this could become an increasingly difficult position.

In sum, the combination of business models in WEEE treatment and refining can distribute risks and rewards on multiple actors (including EEE manufacturers and suppliers), beneficial to maintaining the recycling value chain when treatment costs are high and metals prices low. This is not the case for ELV treatment to the same extent. Hence, the incentives for firms to contribute to metal recycling differ. Business models can thus support recycling of metals from WEEE (T_{F1-2}, T_{C1-2}) in a larger number of scenarios than recycling of metals from ELVs (blocking T_{F3-4}, T_{C3-4}).

5.3. Accumulated industry capabilities: physical capital and knowledge, actors and networks

The capability to convert WEEE and ELVs into metals relies on knowledge of dismantling (skills), the availability of physical capital (e.g. tools, shredding and refining facilities), and firms that organise skilled people and physical capital into working wholes. Since significant resources are required to develop such capability, once established it may be beneficial to continue using it, and to develop it further to reap additional benefits. Hence, current capability does not only decide how well a value chain works at present, but also provides incentives to continue along a certain trajectory, giving rise to path-dependent development (Arthur, 1988; David, 1985; Dosi, 1982).

In the dismantling steps of both WEEE and ELV treatment, dismantling skills are essential. In subsequent segments of the value chains, the use of physical capital intensifies (Reuter et al., 2006; UNEP, 2013). In WEEE treatment, both dismantling and automated treatment steps are partly tuned to the metals being refined in the studied refining facility. In contrast, ELV treatment to a higher degree relies on producing spare parts and raw materials rich in Fe and Al aimed at external actors. There are no observable accumulated pieces of physical capital or highly specific skills dedicated to minor metals in any segments of the value chains. In fact, even if all PCBs would reach refining, minor metals would likely end up in slags (Nakajima et al., 2011).

There are historical roots to these observed structures. The studied metal refining operations date back to the 1930s. Initially Au, Ag, and Cu were mined and refined and during the 40s and 50s operations were extended to include Zn and Pb refining (Boliden, 2014b). In the 1980s, WEEE based raw materials were incorporated when Boliden bought one of the largest WEEE companies (ibid.). In 1991, an automated treatment facility aimed partly at WEEE was installed close to the metal refining facility (Lehner, 2005). ELV treatment has other roots, it was initiated in the 1950s by actors dismantling and selling spare parts, and manually reducing ELVs to pieces of scrap steel. Starting in the 1970s, large scale scrap dealers invested in ELV automated treatment, aimed at generating iron-rich raw materials (Andersson et al., 2017b), and in the 1980s, automated treatment for extracting Al was introduced (Mårtensson, 2015).

In summary, the observed structure of physical capital, knowledge and actor networks has grown over decades, indicating that building value chains require time and resources and that current value chains may not be easily altered. Acquired capabilities will likely strengthen existing trends. In this way, the specialised stocks of knowledge and physical capital in WEEE treatment and refining support recycling of precious metals and Cu from WEEE (T_{F1}, T_{C1-2}). The same stocks block minor metals recovery from WEEE (T_{F2}). The structure of ELV treatment has been tuned to producing spare parts, Fe and Al raw materials (T_{C4}), and is thus less tuned to focal technologies (blocks T_{F3-4}). Additionally, the historic roots of refining also support some contextual technologies (T_{C3}, T_{C5}, T_{C7-8}).

5.4. Long-term industry goals

Long-term goals set by industry actors may motivate new and significant investments in knowledge and physical capital, and thus serve as a supporting factor, since capability and legitimacy are added to a certain system. Although such goals and any associated investments are arguably the result of supporting and blocking factors discussed previously, they also result from independent choices made by industry actors.

In recent years, leading ELV dismantling actors have engaged in improving workshop layouts, testing new dismantling practices and improving waste logistics with the goal of improving operational excellence (Eklund, 2013; IVL Swedish Environmental Research Institute, 2015b). Additionally, finding ways of recovering and selling large plastic components has been the goal for several years since plastics constitute a significant share of the weight of ELVs and often are financially and technically difficult to recycle (SBR, 2011).

Companies involved with WEEE or automated treatment of ELVs have worked to expand or rationalise their collection networks and improve treatment technologies. As part of this, the two largest companies have been reorganising WEEE dismantling points, and long-term investments are made to make automated treatment facilities larger or more efficient (Kuusakoski Oy, 2014; 2015, 2016; Sjölin, 2017; Stena Metall Group, 2015; 2016, 2017). As part of investing in new treatment facilities, one company aims to explore potential future synergies around metals that are now separately generated from WEEE and ELVs (Sjölin, 2017; Stena Metall Group, 2017). Additionally, the two largest companies have set up research facilities in recent years to systematically develop process knowledge (Kuusakoski Oy, 2015; 2016; Stena Metall Group, 2016; 2017). R&D financing is in the order of single digit MUSD/year, indicated by that the largest of the two companies allocates 2–4 MUSD annually (Stena Metall Group, 2015, 2016, 2017).

A stated goal of the refining company is to create synergies between mining and refining operations to produce metals while minimising waste (Boliden, 2017). To this end, expansions and acquisitions of mining operations are made. The three latest ones are aimed at generating Ag, Au, Cu, Ni, Pb, Pd, Pt and Zn concentrates, and are the largest investments ever made by the company at MUSD 730, 475 and 712 respectively (Boliden, 2014a, 2015, 2016a). In comparison, current e-waste refining capabilities cost MUSD 160 (ibid.). Additionally, ca MUSD 60 annually is allocated to R&D (i.e. significantly more than in segments involved with automated treatment), but primarily for investigating mine deposits (ibid.). Although the studied refining facility will continue to support precious metals recycling, these investments indicate that refining operations at large will neither shift away from primary raw materials, nor strongly support minor metals refining in the near future.

In summary, goals among leading ELV dismantling actors seemingly give rise to increasing operational excellence around component dismantling. This can support a development towards recovery of minor components such PCBs, and support recycling of precious and minor metals (T_{F3-4}). Goals by WEEE and automated ELV treatment companies seem to support investment in automated treatment in general, which may serve to make currently working recycling more efficient and potentially create synergies between WEEE and ELV flows. This can support recycling of precious metals from WEEE and ELV (T_{F1}, T_{F3}) but also of other metals (T_{C1-4}). Goals in metal refining lead to mobilisation of resources for refining precious and base metals, mostly from primary resources (T_{C5} and T_{C7-8}). Consequently, different goals throughout the value chains provide mixed support for various focal technologies, but in total seem to be weakly in favour of precious metals recycling from both WEEE and ELV (T_{F1}, T_{F3}) but not so much of minor metals (blocking T_{F2}, T_{F4}).

Table 2
Impact of investigated factors on the four focal technologies T_{F1-F4}. A supporting factor is represented by '+', and a blocking factor not contributing to development or counteracting it by '-'.

Factor	Internal or external	T_{F1} Precious metals from PCBs in WEEE	T_{F3} Precious metals from PCBs in ELVs	T_{F2} Minor metals from PCBs in WEEE	T_{F4} Minor metals from PCBs in ELVs
Metal contents and composition of WEEE and ELV flows	*External*	–	–	–	–
Accumulated industry capabilities	*Internal*	+	–	–	–
Economic potentials of system inputs	*External*	+	+	–	–
Long-term industry goals	*Internal*	+	+	–	–
Political visions and policy-making	*External*	+	+	–	–
Long-term metal price trends	*External*	+	+	–	–
Metal market design	*External*	+	+	–	–
EPR requirements	*Internal*	+	–	+	–
Business models	*Internal*	+	–	+	–

6. Implications for industry and policy

Table 2 summarises the impact of the identified factors on the four focal technologies. The factors and technologies are reorganised, to highlight relative prospects for development and need for additional intervention if further development is desired.

In Section 3.4, we stated that T_{F1} ('WEEE to precious metals from PCBs') is the most mature system. Even if the low metal contents and complex composition of the input, do not work in favour of precious metal recovery, all other factors are more or less supporting. This makes better goal fulfilment possible, or even likely, without intervention.

The technology with second best prospects is T_{F3} ('ELVs to precious metals from PCBs'). The blocking factors 'accumulated industry capabilities', 'EPR requirements' and 'business models' are all internal, and could more easily and directly be affected by national policymakers or industry actors. These factors could also be positively interdependent, meaning that progression in one could stimulate progress in another, and over time result in circular causality and cumulative system build-up.

Recovery of minor metals from PCBs (T_{F2} and T_{F4}) are blocked by both internal and external factors. The combination of relatively low economic potentials of inputs, unfavourable metal markets and long-term price trends, a lack of industry capabilities and goals as well as of political visions and policy-making (in comparison to other technologies) effectively hinder development.

Policy or industry intervention that could mitigate the system internal blocking factors include at least six types, aimed at addressing different socio-technical elements. First, research policy could support capability build-up by investment in formal and practical knowledge, through funding of research, development and demonstration (RDD) projects. Second, industry investment in required new physical capital could be facilitated by enabling access to financial capital at favourable conditions (e.g. through green investment funds). Third, new actors could be incentivised to enter the value chain to accomplish the required specialisations (by e.g. qualifying RDD projects and access to investment funds). For instance, there exists more specialised refining companies already in the EU (European Commission, 2017b), and within Sweden there is small-scale capacity for refining PGMs from catalytic car converters, i.e. recovering specific metals from specific components (Andersson et al., 2017a). Fourth, by more strongly and precisely articulating goals of moving towards circular flows of scarce elements, and mandating relevant political bodies to do so, policy actors would likely affect general expectations in society and may affect long-term industry goal setting and strategies. Fifth, to make EPR regulation more effective, it would need to become more metal-specific. Such targeted requirements have been discussed in Switzerland (Restrepo et al., 2017). Sixth, distributing financial risks among industry actors due to EPR regulations could be improved by altered business models. In WEEE treatment, such risks are shared among EEE manufacturers and suppliers, PROs and WEEE companies. Additionally, the formal procurement procedures used may support terms settlement around metals that today are not considered as business opportunities. Such settlements have been done in WEEE treatment previously to compensate treatment companies for rising costs and fluctuating metal prices (Stena Metall Group, 2016).

However, the above listed interventions would only realise recycling of precious metals, since minor metals recycling is blocked by additional external factors, out of reach for most actors. These external factors include unfavourable conditions in terms of economic potentials, long-term price trends and access to metal markets, which severely diminishes incentives for industry actors to engage in recycling. This might require intervention that leads to changed product designs, to the formation of new markets, or intervention that builds links to existing regional minor metal markets or markets further afield. Additionally, this may have to include (artificially created) high and stable prices. The creation of technology specific markets by targeted price manipulation in particular has proved to be a very effective policy for fostering renewable energy technologies like solar photovoltaics and wind power (Jacobsson and Bergek, 2004; Jacobsson et al., 2004). However, the potentially large geographical distances involved in re-incorporating minor metals into stable markets, such as electronics production, likely demand policy-making at both national and EU levels, and would possibly even have to affect international trade agreements.

It should be noted that, over time, the causal relationships between external and internal factors may change. For instance, a strong development of a T may affect both policy and market conditions such as metal prices. The existence of such effects related to price elasticity, structural industrial change, and institutional response requires further studies, including various forms of modelling and research leveraging thorough knowledge of historic dynamics with relevance for future scenarios (for recent studies dealing with such perspectives, see e.g. Xue-hong et al. (2018), Parker and Cox (2018), Katz and Pietrobelli (2018), or Andersson et al. (2017b)).

In summary, it should be considered that supporting the development of metal recycling requires long-term, high-impact and metal-specific strategies, that target build-up of entire value chains. Developing such strategies likely requires political in-depth knowledge which in turn would require dedicated political bodies aimed at managing elemental resources. Given this, it is notable that in Sweden for example, there is an Energy Agency but no 'Materials Agency' with such capacity.

On a methodological note, by exposing the underlying industry value chains of a 'technology', fine-grained analysis is enabled. In addition, by delineating multiple value chains (i.e. 'technologies'), the TIS approach can be used to study industry development challenges where multiple and potentially conflicting goals are salient features. Finally, in contrast to analyses focusing purely on e.g. technical or economic aspects of recycling, a socio-technical system perspective (such as TIS) may reveal a broad spectrum of problems and corresponding remedies.

7. Conclusions

Due to current material compositions of products, the recycling industry's adaptation to recovery of specific metals, industry business models, and recycling related policy, any recycling of precious metals from ELV PCBs will likely remain challenging in the near-term. However, some challenges may be overcome by imitating current WEEE recycling. Recycling minor metals from ELV or WEEE PCBs will, however, likely remain challenging also in the long-term without significant political metal-specific interventions, aimed at building new industry value chains.

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